TIRE INDUCED SURFACE CRACKING DUE TO EXTREME WHEEL LOADS

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ABSTRACT

Triggered by recurring surface distresses on particular spots at Amsterdam Airport Schiphol, a study was performed into tire induced surface cracking. Calculations focused on traffic in curves at various wheel loads, tire pressures, speeds and curve radii (CROW [1]).

It has been concluded that asphalt failure stresses close to the pavement surface can occur under certain load conditions, and particularly in high speed taxiway and in areas of sharply turning traffic, such as tight push-back operations with lateral wheel slip. However, failure stresses are not necessarily exceeded because of increasing tire pressures, but mainly due to excessive shear stresses imposed onto the pavement surface as a result of high centrifugal forces or rigidity of a multi-axle main gear in tight curves. It can lead to top-down cracking.

Based on linear elastic and visco-elastic VEROAD® calculations and fundamental theory of elasticity for circular loads on an isotropic half space (Gerrard and Harrison, 1970), an analytical model has been developed to analyze the risk of tire induced surface cracking as a function of the tire pressure and the shear stress. The model shows that tire induced surface cracking is solely a material strength issue. The Mohr-Coulomb criterion has been used as the failure criterion. On some issues, the analytical model requires more validation.

Mixture cohesion (c) has been found as the crucial parameter to resist tire induced surface cracking. Cohesion tends to drop with increasing temperatures, which means that the risk of surface cracking is highest during summer. Suggestions have been made for laboratory test to determine mixture cohesion.

A full report of the study is available for a free download from CROW-report D13-01 [1].

INTRODUCTION

Amsterdam Airport Schiphol (AMS) in the Netherlands is handling some 450,000 annual aircraft movements, including a large number of heavy wide-bodies such as the B777 and A340 series of aircraft. The airport is situated in a former lake with a low to ultra-low subgrade strength (subgrade strength category C/D).

The flexible pavement structures generally consist of an SBS PG76-22 polymer-modified asphalt surfacing on a thick high-quality cement stabilized base course. Pavement performance is generally excellent. However, at some locations at the airfield, pavement surface distresses repeatedly occur. These locations are:

- TWY A8, which is a tight curved entry taxiway towards RWY 24, one of the main departure runways;
- TWY A at the location of the F-pier, a heavily used pier for intercontinental wide-body flights. The aircraft are pushed back from the taxi stand to the taxiway.

Both locations have been resurfaced a number of times, but distresses are re-occurring. There is no record of a specific season that distresses are developing. Pavement surface distresses are attributed to tire-pavement interaction, but it is not clear whether the prime cause is related to high tire pressures, high wheel loads, gear configurations or a combination of the aforementioned.

Commissioned by CROW, the Dutch national knowledge source for infrastructure, traffic, transport and public space, the working group 'Tire Pressure Effects on Airfield Pavements' investigated the tire pavement interaction through a literature review and a desk study.

LITERATURE REVIEW

Tire pressure effects on asphalt pavements have been studied and documented by several organizations. The working group has conducted a literature review in order to create a good insight into knowledge on this subject available abroad. Table 1 gives an overview of literature identified by the working group.

Table 1.
Literature on Tire Pressure Effects

Title	Published by	Reference	Date
PCN Publication: Tire Pressure Category Changes – Working Paper	ICAO Aerodromes Panel	AP/2-WP/7	12-10-2010
Full-Scale High Tire Pressure Test on Heated Pavement	FAA Airport Technology Research and Development Team	AJP-6310	31-08-2010
High Tire Pressure Test Technical Report	Airbus	X32RP0926801	31-08-2010
High Tire Pressure and Temperature Effects on Hot Mix Asphalt Concrete Permanent Deformation using Customized Asphalt Pavement Analyzer (APA)	Song and Garg	2010 FAA Worldwide Airport Technology Transfer Conference	April 2010
Evaluation of Pavement Damage due to New Tire Design	Wang and Al-Qadi	Illinois Center for Transportation Research Report ICT-09-048	May 2009
Impact of Non-Uniform Aircraft Tire Pressure on Airfield Pavement Responses	Wang and Al-Qadi	ASCE Conf. Proc. 10.1061/41167 (398)81	March 2011
Unified Constitutive Model for Airport Pavements	Desai, Rigby, & Samavedam	Airport Pavement Innovations. Theory To Practice. Conf. Proc. ISBN: 0-87262-925-2	September 1993
A Novel Approach to Develop a Performance Based Test for Rutting of Asphalt Concrete	Meegoda and Chang	Airport Pavement Innovations. Theory To Practice. Conf. Proc. ISBN: 0-87262-925-2	September 1993

With regard to the impact of high tire pressures on the performance of asphalt pavements, the literature reviewed does not draw unambiguous conclusions.

Full-scale research by Airbus and FAA/Boeing did not reveal a significant impact of increased tire pressures on pavement rutting. Pavement performance was more affected by increased wheel loads and pavement temperatures than increased tire pressures from 1.5 to 1.7 MPa. The results of both full-scale tests were not supported by theoretical analysis or laboratory research. Test considered moving wheel loads in a straight line at constant speed.

Tire pressure effects on pavement rutting were observed by Song and Garg [2] using the Asphalt Pavement Analyzer (APA). However, increase of tire pressure was achieved in these tests by increasing the load while keeping the same contact area.

Wang and Al-Qadi [3] have concluded in their theoretical research by FE-modelling that there is a significant impact by the tire stress distribution on the pavement surface performance. Non-uniform stress distributions under radial tires could cause 30-60% increase in shear stresses and strains in the pavement surface. Increase of tire pressure did not cause any significant increase in stresses and strains.

PAVEMENT AND LOAD CHARACTERISTICS

The desk study comprised linear elastic and visco-elastic calculations with various loads on a pavement model similar to the structure at Amsterdam Airport Schiphol. The visco-elastic model for asphalt was based on the Burger's model as shown in Figure 1.

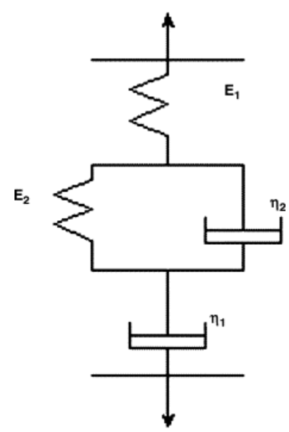


Figure 1. Burger's Model

The characteristics of the pavement structure are shown in Table 2, whereas the asphalt is modelled as an elastic layer (1a) or a visco-elastic layer (1b).

Table 2.
Pavement Structure Details

Layer	Material	Material Model	Material Parameter	Thickness
1a	Polymer Modified Asphalt	elastic	E = 7000 MPa (@ 8 Hz, 25 °C) ν = 0.35 c = 1.0 MPa φ = 35°	200 mm
1b	Polymer Modified Asphalt	visco-elastic	E_1 = 9,000 MPa E_2 = 9,000 MPa η_1 = 200 MPa.s η_2 = 200 MPa.s ν = 0.35 c = 1.0 MPa φ = 35°	200 mm
2	Cement Treated Base Course	linear elastic	E = 5,000 MPa	700 mm
3	Clayey Subgrade	linear elastic	E = 40 MPa	∞

Calculations were carried out with single wheel loads as per Table 3. The combined effect of multiple wheels has been considered, but was found to be insignificant.

Table 3.
Load Characteristics

	Straddle Carrier	**Aircraft Tire B737**	**Aircraft Tire B777**	**High Pressure Tire**
Wheel load	19 t	19 t	25 t	25 t
Tire pressure	0.86 MPa	1.45 MPa	1.54 MPa	1.75 MPa
Contact radius	265 mm	204 mm	227 mm	213 mm

Load (vertical and horizontal) were uniformly distributed over the circular contact area (Figure 2).

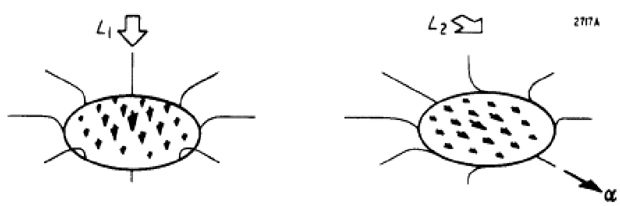


Figure 2. Vertical Pressure and Horizontal Shear Stress

For calculations in curves, a normal taxiway curve has been considered with a 55 m centerline radius and the curve that is followed by the main gear during a push-back operation, when the aircraft is pushed by a tractor from its parking position to a taxiway. Both situations are representative for the damage cases reported at Amsterdam Airport Schiphol.

Assuming that aircraft are taxiing according to the standard procedure with the cockpit over the centerline of the normal 55 m taxiway curve, the inner main gear leg of a B777 aircraft will follow a curve with a radius of approximately 35 m, as can be derived from the airport planning manual for the B777 (B777 Planning Manual).

Under normal circumstances, a push back operation is carried out with an aircraft nose wheel steering angle of not more than 55 degrees. The corresponding radius of the inner main gear leg is 15 m in this case. In extreme cases the maximum steering angle may be touched during a push-back. In such case the corresponding radius of the inner main gear leg is 4.7 m, say 5 m.

FAILURE MODEL

For the analysis of stresses and strains in the asphalt layers, homogeneous isotropic material behavior has been assumed. Taking the theorem that asphalt failure occurs when the Mohr-Coulomb criterion is exceeded, the calculate stresses are subject to a Mohr-Coulomb analysis. In a graphical form, the normal and shear stresses as well as the corresponding Mohr circle can be plotted in a diagram (Figure 3).

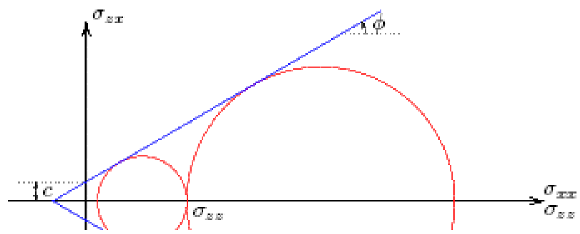


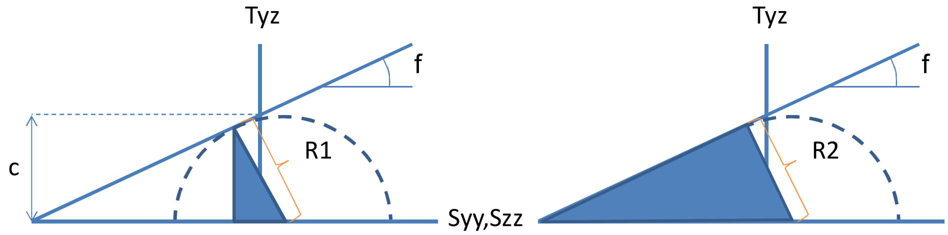
Figure 3. Mohr-Coulomb Diagram

When the Mohr circle touches the Coulomb envelop, failure occurs. In order to have an indication on the safety margin between the actual stress state (Mohr circle) and the failure limit (Coulomb envelop) a factor of safety has been introduced, hereafter called the 'structural robustness factor' or F_{SR}.

The structural robustness factor F_{SR} is the factor at which the tire pressure can be increased (hence, increasing wheel load with constant contact radius) until the stress state in a certain point within the asphalt touches the Coulomb envelop. F_{SR} can be calculated as follows:

$$F_{SR} = c \times \cos(\phi) \times \left(\sqrt{\left(\tfrac{1}{2} S_{zz} - \tfrac{1}{2} S_{yy}\right)^2 + T_{yz}^2} + \tfrac{1}{2}\left(S_{zz} + S_{yy}\right)\sin(\phi) \right)^{-1}$$

The equation for F_{SR} can be derived based on uniformity of two triangles in the Mohr-Coulomb diagram at the moment of failure. This is graphically represented in Figure 4.



$$R1 = F_{SR}\sqrt{\left(\tfrac{1}{2}S_{zz} - \tfrac{1}{2}S_{yy}\right)^2 + \left(T_{yz}\right)^2} \qquad R2 = \left(\frac{c}{\tan(\varphi)} - F_{SR}\frac{\left(S_{zz} + S_{yy}\right)}{2}\right)\sin(\varphi)$$

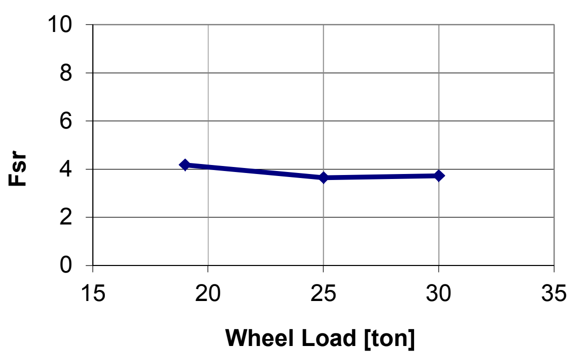
$$R1 = R2$$

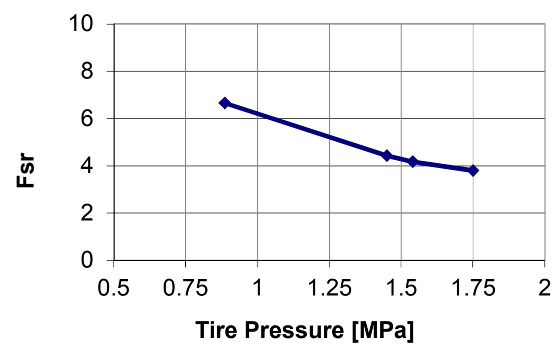
Figure 4. Schematic for F_{SR} Equation

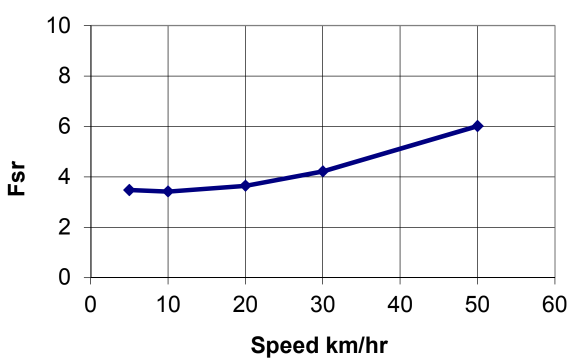
In case $F_{SR} < 1$, failure is likely to occur. $F_{SR} = 2$ indicates that either the wheel load can be doubled, or the material strength may decrease by 50% until failure occur. In case there are no normal tensile stresses in the asphalt (e.g. the Mohr circle is entirely on the positive side of the X-axis), then the F_{SR} reaches infinity (∞).

STRAIGHT MOVING LOADS

The calculation results for straight moving loads are shown in the following four diagrams where F_{SR} is plotted against variable wheel load, tire pressure and speed.







- Variable wheel load at fixed tire pressure of 1.54 MPa
- Variable tire pressure at fixed 19 t wheel load
- Variable speed at fixed wheel load of 25t at 1.54 MPa

Figure 5. F_{SR} for straight moving loads

In all cases for straight moving loads the F_{SR} remains far above the failure condition defined as $F_{SR} < 1.0$. The effect of changes in pavement structure have not been investigated, but so far the conclusion is justified that straight moving loads will not cause surface induced cracking in asphalt pavements.

LOADS IN CURVES

For a 25t wheel at 1.54 MPa tire pressure, calculations have been made for loads acting curves, thus imposing a horizontal shear force to the pavement surface. The first set of calculations was made for a curve radius of 35 m, corresponding with the radius of the inner main gear of a B777 traversing a standard 55 mm taxiway curve. Horizontal shear (τ) was calculated as a function of speed (v), wheel load (m) en curve radius (R) using the following equation:

$$\tau = m\frac{v^2}{R}$$

The resulting shear stresses are as follows:

Table 4.
Horizontal Shear as a Function of Speed

Speed	Horizontal shear at tire-pavement interface	Horizontal G-force
20 km/hr	0.14 MPa	0.09 g
30 km/hr	0.31 MPa	0.20 g
34 km/hr	0.39 MPa	0.26 g
50 km/hr	0.85 MPa	0.56 g

The resulting F_{SR} due to above stresses are shown below.

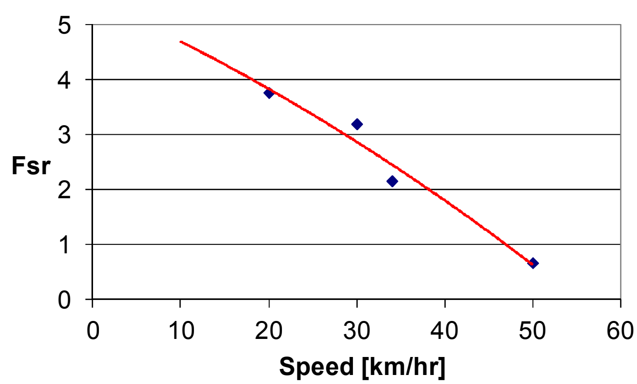


Figure 6. F_{SR} as a Function of Speed for B777 at 1.54 MPa and r = 35 m

From this picture one could conclude that (given the structure parameters as per Table 2), the asphalt is likely to fail if a B777 traverses a 35 m radius curve at speeds higher than 40 km/hr. It has to be realized that such speeds are quite high, considering the G-forces that will act on the aircraft (Table 4). Hence, if such a condition occurs, it will happen in extreme cases only.

Another set of calculations were made to simulate push-back operations at 10 km/hr following a tight 10 m radius curve as described previously. The resulting F_{SR} as a function of tire pressure is shown in Figure 7.

In all cases, the F_{SR} is well above unity. Apparently, a normal push-back maneuver does not induce stress conditions that could result in surface damage, even at high tire pressures. Even when using extreme steering angles the curve radius could be as small as 5 m, but it is highly unlikely that a 5 m radius curve is traversed at 10 km/hr. Therefore, one could conclude that normal push-back operations cannot be the reason for tire induced surface damage.

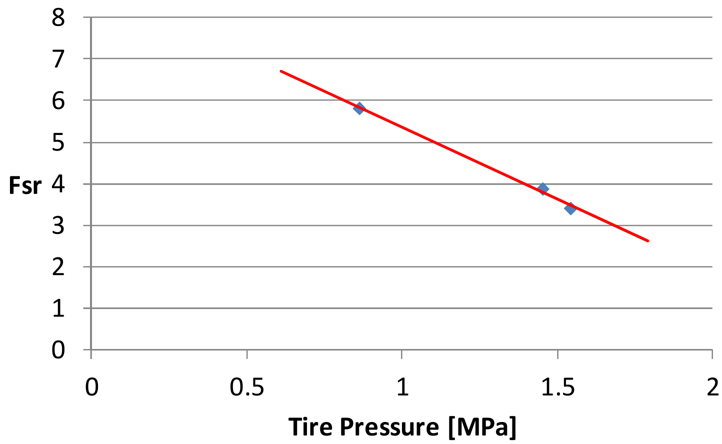


Figure 7. F_{SR} at Low Speed (10 km/hr) and Tight Curve (r=10m) as a Function of Tire Pressure

The last stress mode under study is shear stress due to rigidity of main gears. The gear dimension of a B777 main gear leg is around 3.0 m in length and 1.5 m in width, covering a 6-wheel configuration in three axles. In order to reduce the tear and wear at a main gear leg in small curves, the last axle has a steering ability, which is shown in the figure below. Still, the frame of the two front axles is rigid, which means that in tight curves horizontal shear forces are induced at the pavement surface because of the misalignment of the two front axles in relation to their pivot point.

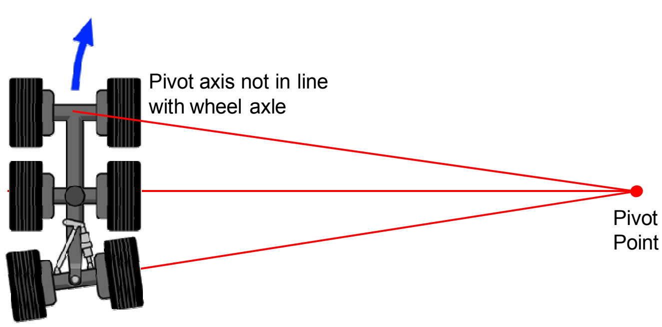


Figure 8. B777 Multi-Axle Pivot Point

These shear forces are not because of centrifugal forces (as considered in the previous paragraphs), but as a result of axles following the same curve with different pivot points. In extreme cases, the horizontal shear could cause lateral slip of one or more wheels.

Lateral slip means that the friction coefficient between tire and pavement is exceeded. Two calculations have been done with a B777 wheel at 10 km/hr and a maximum friction coefficient of 0.4 and 0.8, respectively. At the B777 tire pressure of 1.54 MPa, the resulting shear stress is therefore 0.62 and 1.23 MPa, respectively.

In the case of a 0.4 slip factor, the F_{SR} is just tipping a value 1.0. At 0.8 slip factor, the F_{SR} drops to 0.4. Hence, in both cases the critical failure stresses are exceeded at the inner edge of the wheel. The chosen slip factors may be realistic, especially in dry surface conditions.

From the above, one could conclude that extreme push-back operations, resulting in lateral wheel slip, are likely to cause tire induced surface damage.

KEY TRIGGER TO SURFACE DAMAGE

Various parameters have been identified that play a role in causing surface damage, i.e. tire speed, curve radius, tire pressure and slip factor. The results of all calculations have been correlated in various ways in order to find the strongest trigger of tire induced surface damage. The strongest correlation was found when F_{SR} was plotted as a function of the imposed shear stress. This is shown in Figure 10 below.

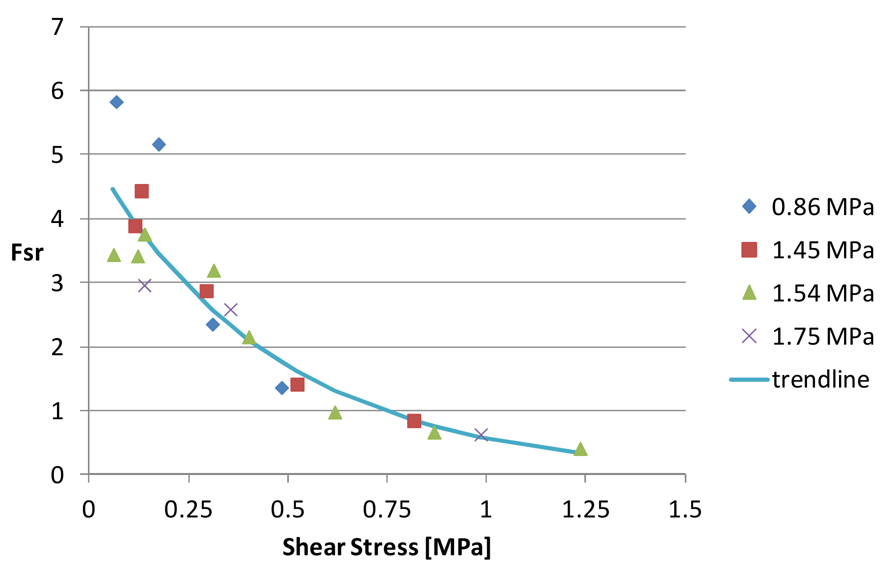


Figure 9. F_{SR} as a Function of Horizontal Shear Stress

The correlation of F_{SR} at shear stress levels beyond 0.25 MPa seems to be rather strong. At shear stress levels beyond 0.5 MPa, the F_{SR} enters the critical zone where surface damage is likely to occur ($F_{SR} < 1.0$). The most remarkable conclusion, however, is that F_{SR} seems not to be directly related to tire pressure. In other words, no matter how high the tire pressure is, when the shear stress exceeds 0.5 MPa, surface damage is very likely to occur. Obviously, it is easier to reach the 0.5 MPa shear stress level at higher tire pressures. In this way, high tire pressure is contributing to the distress of top-down cracking.

ANALYTICAL MODEL TO PREDICT CRITICAL STRESSES

Gerrard and Harrison [4] developed analytical solution to calculate stresses, strains and displacements for various circular loads to a cross-anisotropic half space. These circular loads comprised amongst others uniform vertical pressure and uniform unidirectional shear.

For the purpose of this study, only the solutions for the stresses σ_{zz}, σ_{yy} and τ_{yz} are shown for the following special conditions:

- The half-space is isotropic and linear elastic;
- Stresses are calculated at depth z = 0;
- Stresses are calculated just inside the edge of the wheel and just outside the wheel.

The combined stresses of vertical pressure and horizontal shear are the sum of the analytical solutions for the individual loads.

Table 5.
Analytical Solution Edge of Wheel at z = 0 mm

	inside wheel	outside wheel
σ_{zz}	$\sigma_{zz} = TP$	$\sigma_{zz} = 0$
σ_{yy}	$\sigma_{yy} = -TP\left(\nu + \frac{1}{2}\right) - 2HS\left(\alpha + \frac{2\nu}{3\pi}\right)$	$\sigma_{yy} = -TP\left(\nu - \frac{1}{2}\right) - 2HS\left(\beta + \frac{2\nu}{3\pi}\right)$
τ_{yz}	$\tau_{yz} = HS$	$\tau_{yz} = 0$

Where:
TP = tire pressure [MPa]
HS = horizontal shear stress [MPa]
ν = Poisson's ratio
α, β = Gauss's hypergeometric function of the y-coordinate

For the condition y = wheel radius, α and β tend to go to infinity, which implies that the limit of σ_{yy} is infinite. This would imply that the asphalt will already fail under very small shear loads. The σ_{yy}-curve close to the wheel edge shows very steep slopes. Hence, σ_{yy} changes rapidly around the wheel edge, which makes the α- and β-factor very sensitive to the location under the wheel. For the stresses just outside the wheel, β = 0.6 shows a fairly good match for the higher shear stress levels resulting in $F_{SR} \leq 1$. However, for low shear stress levels ($F_{SR} > 2$) the correlation shown below is rather poor.

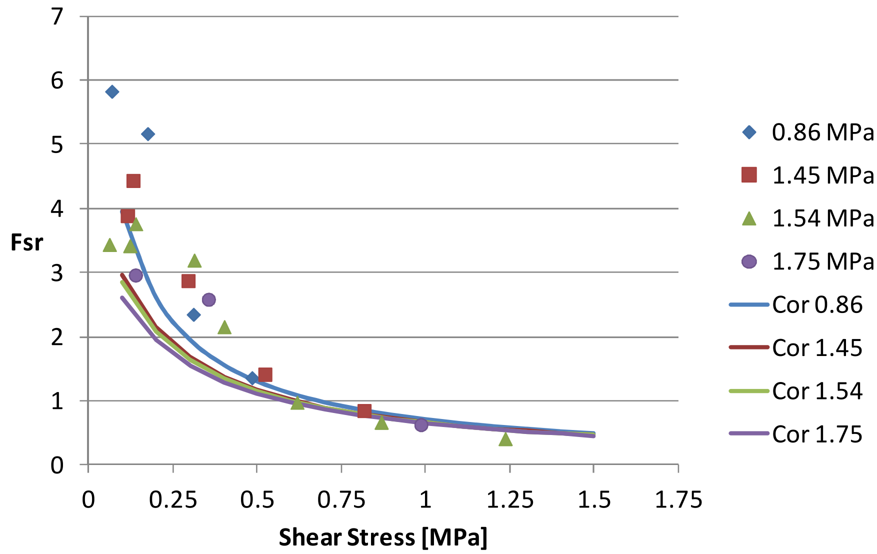


Figure 10. Analytical Model Plotted in Numerical Calculation Results

Despite the mismatch at lower shear stress levels (which can be regarded conservative, hence with a 'safe' F_{SR}), the analytical approach helps identifying and understanding the important parameters for tire induced surface cracking:

- Stresses at z = 0 mm are independent from material elasticity (E-modulus). Therefore, not material stiffness but only Poisson's ratio is of importance;

- The key variables in the analytical approach are: tire pressure, horizontal shear stress, Poisson's ratio, cohesion (c), angle of internal friction (φ);

- Tire induced surface cracking is solely a material strength issue, so if material strength parameters c and φ are known, then one can predict the risk of surface cracking;

- The contribution of tire pressure diminishes as shear stress increases.

It is important to remember that $F_{SR} = 1$ indicates instantaneous failure due to a single load. Hence, the repetitive loading and consequential fatigue effects are ignored if $F_{SR} = 1$ is taken as the condition for failure. Fatigue effects for surface cracking have not been studied. It is recommended to maintain a reasonable factor of safety in surface cracking calculations in order to account for fatigue. Which value to be used for F_{SR} is an engineer's judgment at this stage.

When looking at the stress state just outside the wheel, then the analytical solutions show that $\sigma_{zz} = \tau_{yz} = 0$. Taking the failure condition $F_{SR} = 1$, the failure model presented earlier reduces to a simple equation. Substituting σ_{yy} in this equation by the analytical solution for σ_{yy} outside the wheel, results in the failure condition for any combination of tire pressure and shear that fulfils the equation. This failure condition is represented by the following equation and by the Mohr-circle in Figure 11.

$$TP\left(\nu-\tfrac{1}{2}\right)+2HS\left(\beta+\frac{2\nu}{3\pi}\right)=-\frac{2c\cos(\varphi)}{(1+\sin(\varphi))}$$

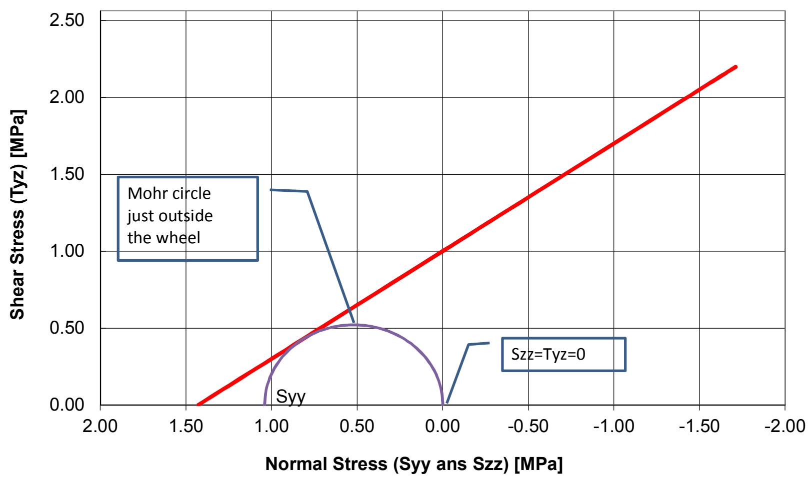


Figure 11. Stress State at Failure, just Outside Wheel

IMPORTANCE OF MIXTURE COHESION

Assuming that the angle of internal friction of an asphalt mix (φ) is fairly constant (32-38 degrees), the mix cohesion (c) is the most important parameter to be determined. Research into asphalt rutting behavior (Christensen et al [5] and Zaniewski [6]) has shown that the Indirect Tensile Strength (ITS) test is a simple test to determine cohesion. If one would assume a Poisson's ratio of 0.5, then the compressive stress at failure would be three times the tensile stress, $\sigma_z = -3\sigma_y$. This can also be plotted as a Mohr circle.

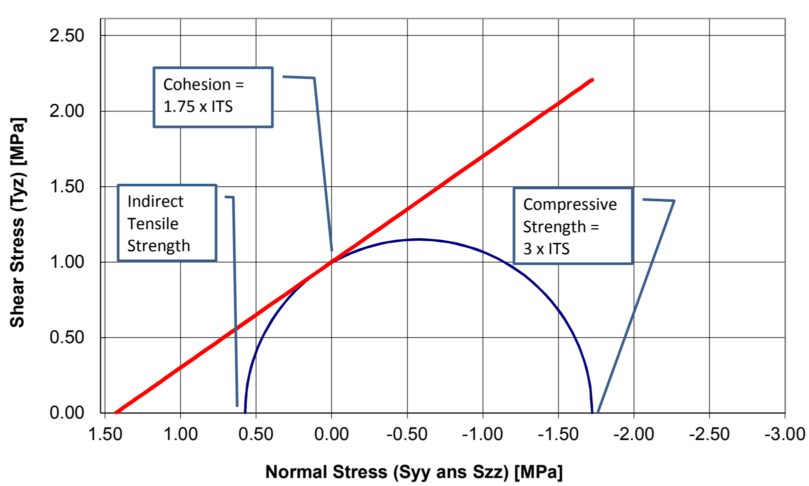


Figure 12. Coulomb Failure Line from Indirect Tensile Strength Test

From this Mohr-circle, one can obtain the cohesion being 1.75 x indirect tensile strength. The correctness of this equation is shown with test data below, showing a very strong correlation. It should be noted that an ITS-test is a fairly simple but accurate test to determine mixture cohesion. Failure related to asphalt mixture properties can easily be assessed.

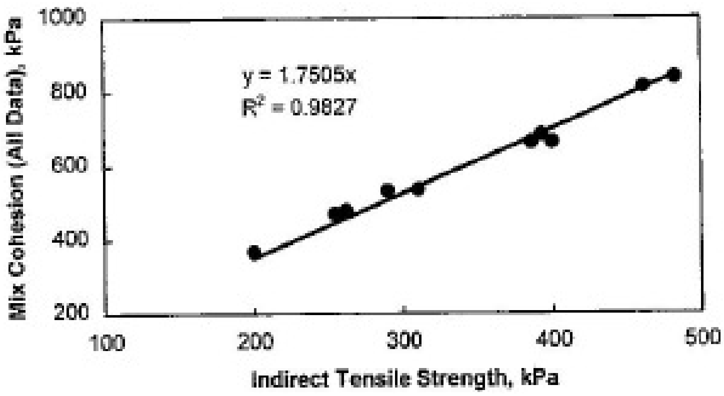


Figure 13. Correlation between ITS and Cohesion (Christensen [5])

All calculations in this paper have been performed at an assumed cohesion c = 1.0 MPa. ITS-test data collected from various projects show a significant drop in ITS with increasing temperature as shown in Figure 14 for various binder types. Considering the above relation between cohesion and ITS, the corresponding ITS for all calculations in this paper would be 1/1.75 = 0.57 MPa.

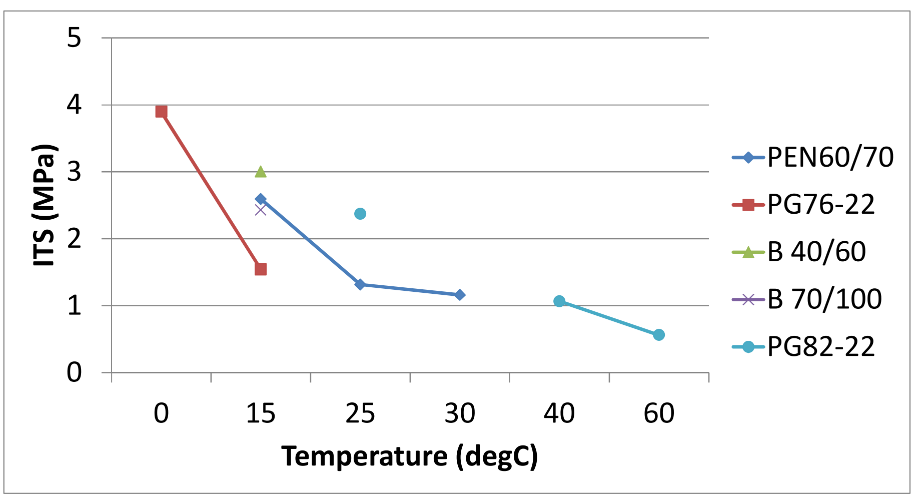


Figure 14. Average ITS as a Function of Temperature for various Binder Types

Figure 14 shows that the ITS drops to critical values at high asphalt temperatures. The population of test data for the PG82-22 binder at 40 and 60 degrees Celsius is rather limited, so results should be interpreted with care. However, an important conclusion can be drawn that surface cracking due to shear stresses is likely to occur at high asphalt temperatures due to loss of mixture cohesion.

CONCLUSIONS

The risk of tire induced surface cracking as a function of tire pressure and shear stress has been investigated.

1. Extreme but realistic combinations of tire pressure and shear stress have shown that surface failure is likely to occur under certain conditions.
2. It has been concluded that tire induced surface cracking is a material strength and not a material stiffness issue. The Mohr-Coulomb criterion has been used as the asphalt failure criterion.
3. Surface cracking is mainly caused by horizontal tensile stresses at the edge of the wheel exceeding the asphalt strength. At arbitrarily chosen values for c and φ of 1.0 MPa and 35°, mixture cohesion (c) has been found as the crucial parameter to resist tire induced surface cracking.
4. Cohesion tends to drop with increasing temperatures, thus increasing the risk of surface cracking at higher temperatures.
5. In order to be able to quantify the risk of failure, cohesion data need to be collected at elevated temperatures. The Indirect Tensile Strength (ITS) test appears to be a simple and decicive test to determine cohesion. ITS can easily be used in selecting better performing asphalt mixtures.

RECOMMENDATIONS

1. An analytical model has been developed to analyze risk of surface failure. The model gives clear insight into the important parameters, but it requires further validation. This is mainly because of the rapid change of tensile stresses close to the wheel edge.
2. Tire pressure and shear stress are assumed to be uniformly distributed over a circular area. Desai, Rigby, & Samavedam [7] have shown that non-uniform stress distributions under radial tires could cause 30-60% increase in shear stresses in the pavement surface compared to uniform distributions. The effect of non-uniform stresses shall be further studied. Reference is made to Jacob's dissertation [8] for a model to simulate non-uniform tire distributions.
3. Failure is defined as per the Mohr-Coulomb criterion, which means that failure occurs due to a single loading event. Fatigue phenomena for surface cracking due to repetitive loading shall be studied in more detail.
4. Influence of interface condition between two asphalt layers needs to be investigated as loss of bond between asphalt layers is known to be a cause of cracking.
5. Shape of the tire contact area has been assumed circular. Impact of rectangular or ellipse-shape contact areas needs to be investigated.

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